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FRICTION-TYPE BOLTED CONNECTIONS WITH A588 WEATHERING STEEL

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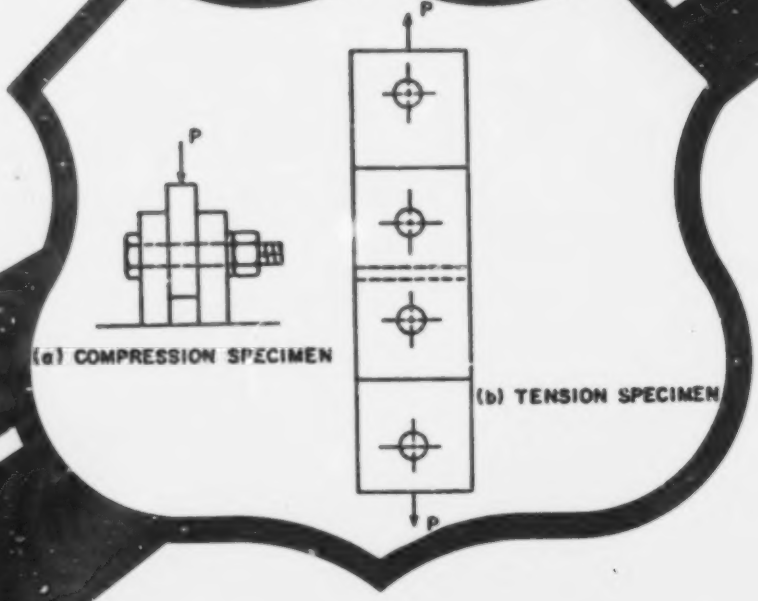
December 1981
Final Report



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FOREWORD

The use of high-strength bolts as connectors has produced bridge structural joints of superior quality and economy. However, the corrosion of untreated faying surfaces of friction-type bolted connections in steel bridges often results in joint separation and/or reduction of the coefficient of friction. Corrosion inhibiting coatings used on the faying surfaces or other forms of surface treatment such as blast-cleaning, can increase the slip resistance as well as reduce the scatter in the slip performance of a bolted joint.

Design recommendations and possible revisions in the AASHTO Bridge Specifications are presented. This is one of two final reports on the results of this research that are being distributed to the Washington and field offices of the Federal Highway Administration, State highway agencies and interested researchers. The other report is FHWA/RD-81/148, "An Experimental Study of Bolted Shear Connections."

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

NOTICE

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design, or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

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16. Abstract

One hundred twenty-six slip tests were conducted on friction-type bolted connections fabricated from A588 weathering steel. The tests were conducted mainly on specimens with mill scale or blasted surfaces which were exposed to the atmosphere for periods up to one year.

The test results indicate that A588 mill scale surface has a 33 percent lower slip resistance than those reported for other steels. Suggested revisions to the AASHTO Bridge Specifications based on this behavior are presented.

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1. INTRODUCTION

The principal variable that affects the slip resistance of the contact surfaces in a high-strength bolted connection is the slip coefficient (k_s) which is an indicator of surface friction. There are currently no reliable theoretical models for predicting slip resistance, so experiments on small connections are conducted to determine the slip load. The experimental k_s is calculated as

$$k_s = \frac{\text{slip load}}{\text{clamping force} \times \text{number of slip planes}} \qquad (1)$$

Most slip specimens used to date have a main center plate and two side plates; such butt-type bolted connections have two slip planes.

A summary of slip coefficients for various steel types, surface treatments and surface coatings is presented in Ref. 1. These data have been used to develop the allowable bolt shear stresses in friction joints which appeared in the Specification for Structural Joints Using ASTM A325 or A490 Bolts, hereinafter referred to as the Bolt Spec, in 1976 [2]. The American Association of State Highway and Transportation Officials (AASHTO) reduced the Bolt Spec values by about 10 percent and incorporated them into the 1978 Interim Bridge Specifications [3]. The AASHTO design recommendations are reproduced in Table 1. Values given for surface classes A, B, and C, which refer to unprotected steel surfaces, were based on over 700 slip tests for steels with specified yield points between 33 ksi (228 MPa) and 100 ksi (690 MPa). Some specimens were exposed to the atmosphere to permit surface corrosion prior to assembling and testing.

None of the documented slip tests were conducted on ASTM A588 steel (weathering steel) which is very common on bridge structures. ASTM A588 steel is used in exposed environments with mill scale, blasted and painted surface conditions. Tests have indicated that the type of steel has little effect when the surfaces are painted [4], so the recommendations for Classes D through I in Table 1 should be applicable to A588 steel. The bare steel condition (mill scale and blasted) may show some differences for A588 steel, since the steel surface condition which provides the improved corrosion resistance is different from other structural steels. In addition, no data are available on A588 steel to address the issues of effect of exposure on slip resistance and the effect of faying surface corrosion on the bolt clamping force.

An experimental program was undertaken to determine the slip characteristics of connections using A588 steel. Static slip tests and creep tests were conducted on connections with blasted and mill scale surfaces. Some joints were weathered over time intervals up to one year. Bolt forces were monitored on the exposed creep tests. Different grades of A588 steel [5] as well as different heats of steel within a certain grade were studied so that design recommendations would represent the

variations to be expected. A total of 126 slip tests were conducted.

In the subsequent sections, the test program and results are presented. The results are compared to those obtained for other structural steels, and design recommendations for friction connections in bridge structures using A588 steel are developed.

Table 1. Allowable bolt shear stresses in ksi. 1978 AASHTO Interim Bridge Specification (abridged).

(1 ksi = 6.9 MPa)

Class of Surface	Surface Condition of Bolted Parts	Standard Holes		Oversize Holes and Short Slotted Holes	
		A325 Bolts	A490 Bolts	A325 Bolts	A490 Bolts
A	Clean mill scale	16.0	20.0	13.5	17.0
B	Blast-cleaned carbon and low alloy steel	25.0	31.0	21.0	26.5
C	Blast-cleaned quenched and tempered steel	17.0	21.0	14.5	18.0
D	Hot-dip galvanized and roughened	19.5	24.5	16.5	20.5
E	Blast-cleaned, organic zinc rich paint	19.0	23.5	16.0	20.0
F	Blast-cleaned inorganic zinc rich paint	26.5	33.5	22.5	28.5
G	Blast-cleaned, metallized with zinc	26.5	33.5	22.5	28.5
H	Blast-cleaned, metallized with aluminum	27.0	34.0	23.0	29.0
I	Vinyl wash	15.0	18.5	12.5	16.0

2. EXPERIMENTAL PROGRAM

Program Variables

A test program was designed to provide statistically valid experimental slip data for friction connections with A588 steel. The program was devoted principally to connections with unprotected surfaces, both mill scale and blasted, and the effect of surface corrosion on the slip characteristics. A few pilot tests were designed to investigate the significance of what were presumed to be minor effects related to creep, paints on A588 steel, and changes in bolt clamping forces. Both tension type and compression type slip tests were considered. A schematic diagram summarizing the slip test program is shown in Figure 1. The number of tests conducted is shown in parentheses. In general, five replicate specimens were tested for each principal variable. The experimental work was conducted at two separate agencies, The University of Texas at Austin (UT) and the Federal Highway Administration (FHWA).

Steel. There are nine different grades (A through J) of A588 steel based on variations in their chemical composition. However, all minimum physical requirements such as yield point and tensile strength are the same for all grades. Three different heats from Grade A, and two heats from Grade B were used in the study. One heat of A588 Grade A was used for all tests conducted at the University of Texas and is identified as Steel A1. The remaining two heats of Grade A (Steels A2 and A3) and the two heats of Grade B (Steels B1 and B2) were used in the FHWA tests. All steel was purchased on the open market. Chemical analyses and tensile coupon tests confirmed that the steels satisfied the chemical and physical requirements for A588 steel. The connection test results from the five heats of A588 steel should provide a reasonable indication of the mean slip coefficient and its variation.

Surface Conditions. In bridge structures, A588 steel is used with mill scale, blasted, and painted surface conditions. Because other research had shown that steel type had no effect when the surfaces were painted [4], all but two of the 126 slip tests were conducted on mill scale or blasted surfaces. All blasted plates for the UT tests were dry sandblasted with a No. 3 blasting sand (fine) to a white metal condition. Plates for the FHWA tests were grit-blasted to white metal using a 100 mesh aluminum oxide. Fifty-five connections had mill scale surfaces, 29 were sandblasted, and 40 were grit-blasted. All sandblasting was done at one time; a similar situation was arranged for the grit-blasting. Prior to assembling the connection, the faying surfaces were cleaned with acetone to remove any oil, blasting particles, or dust.

Two connections with zinc-rich primer, one organic and the other inorganic, approximately 5 mils thick on each steel surface were tested. The paints were the same as those used by Fouad [4] in another study, a modified single package organic zinc-rich phenoxy and a two-component silicate base inorganic primer, both of which satisfied the Structural

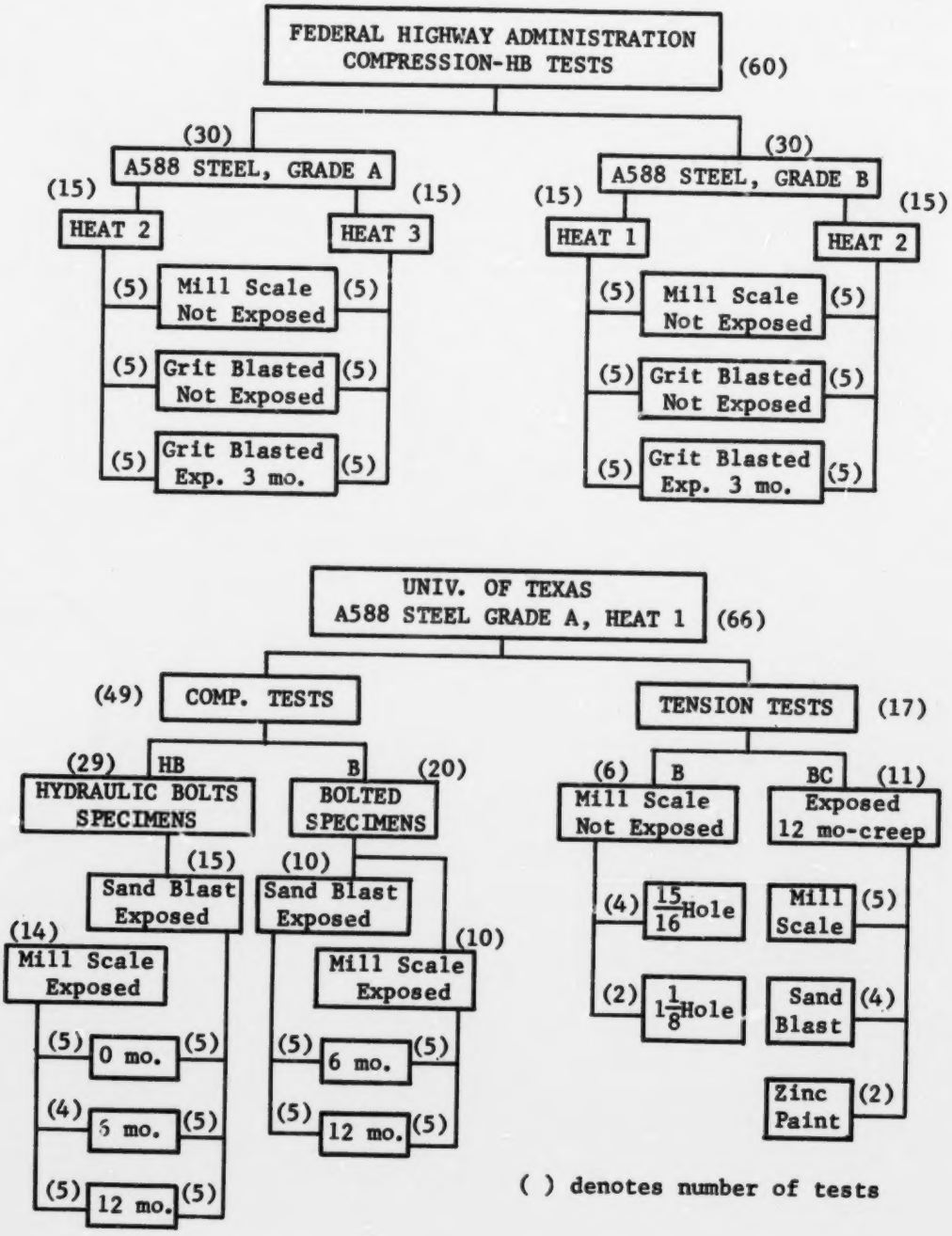


Figure 1. Slip test program

Steel Painting Council Specification (SSPC-PS 12.00-68T). On both connections the zinc primer was sprayed in multiple coats to the desired dry thickness on a surface sandblasted to a white condition which satisfied the paint manufacturer's surface treatment recommendations.

Exposure. A variety of questions given below, which are related to exposure to the atmosphere of the A588 connections or their components at various stages of fabrication and construction, were considered in the design of the experimental program.

1. How is the slip resistance affected if the connection components are exposed in open air prior to assembly (field connection)?

2. Is the slip load affected by exposure after the connection is assembled?

3. Will faying surface corrosion after assembly affect the tensile load in the bolt?

4. Is there any effect on slip resistance if there is a significant applied shear load on the assembled condition during exposure? Is the rate of surface corrosion affected by the applied load?

The test program at UT was principally devoted to the exposure effects. Three categories of specimens were developed to resolve these questions:

(a) Unassembled plates. These plates (three per test connection) were suspended vertically on outside racks by wires through the bolt hole, as shown in Figure 2. Details of these specimens called HB connections are presented later. The connection was assembled for testing after the desired exposure had taken place.

(b) Bolted connections (designated B connections) shown in Figure 3 in which the plates were assembled with a 7/8 A325 bolt (22 mm) prior to exposure with no shear load applied during exposure. These specimens were also suspended from the rack.

(c) Creep specimens (BC connections) which were assembled with tightened A325 bolts prior to exposure and subject to a constant shear load in the chain-like setup shown in Figures 4 and 5.

In the UT program the specimens were left continuously in the open air until testing during the period September 1977 through August 1978. The specimens were exposed to 23 in. (580 mm) of rainfall and periodic wetting with Austin city water (alkaline) during dry spells. Normal Austin rainfall is in excess of 30 in. (760 mm) per year and humidity

Figure 2. Exposure racks

Figure 3. B connections, bolted prior to exposure

Figure 4. Creep chain test setup

Figure 5. Creep chain specimen (BC connections)

is usually less than 70 percent. Nineteen slip tests were conducted after 6 months exposure, 31 tests after 12 months exposure.

In the FHWA program five grit-blasted specimens from each heat of steel were exposed to the Washington, D.C. atmosphere for a period of 3 months (September 1, 1978 to November 30, 1978) prior to assembly and testing. During this period, 4.5 in. (114 mm) of rainfall were recorded and the relative humidity was typically 64 percent.

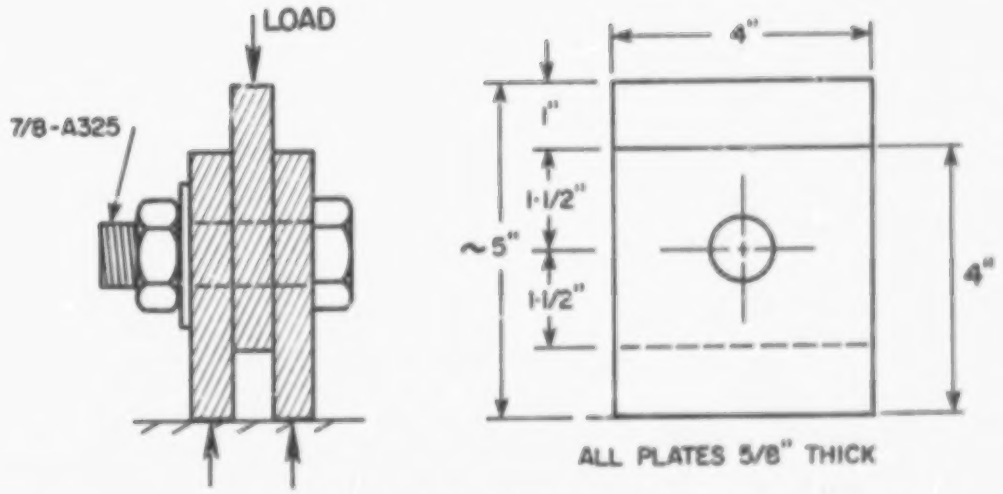
Test Specimens and Arrangement

Four different test specimens using two different test arrangements (compression test or tension test) were developed to meet the program objectives. The details of the specimens are given in Figures 6 through 8.

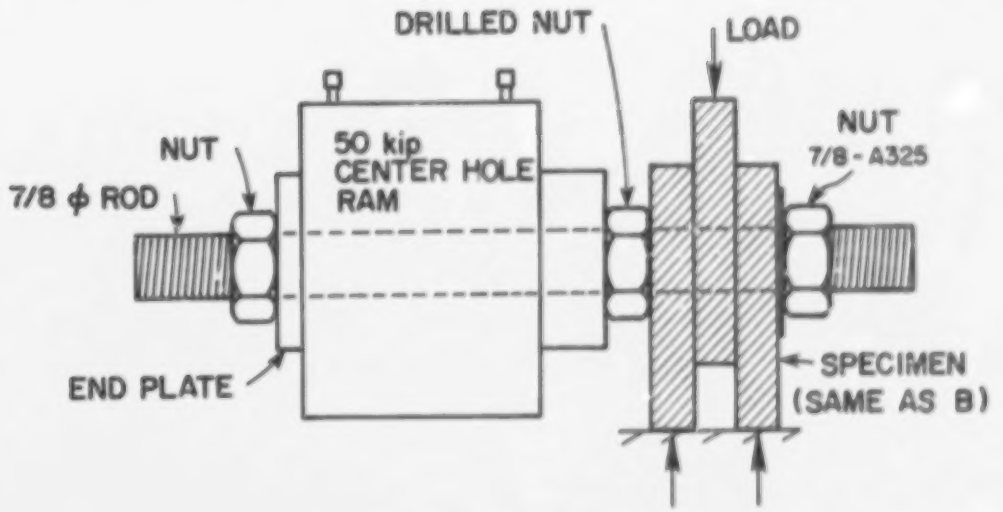
All specimens were constructed from 5/8 in. × 4 in. (16 mm × 102 mm) A588 steel bar stock and the contact surface area was 4 in. × 3 in. (102 mm × 76 mm). One hundred twenty-four specimens had 15/16 in. (24 mm) holes to accommodate the 7/8-in. (22 mm) diameter fastener; two specimens had 1-1/8 in. (29 mm) diameter oversize holes with 7/8 A325 bolts (22 mm). A hardened washer was used under the nut. Both compression type and tension type specimens were used because of convenience and also to determine if the type of test affects the slip load. Some limited previous data indicated that the type of test did not significantly influence the slip load [6]. All connections were assembled with the fastener in bearing in a direction opposite to the planned loading to ensure obvious slip deformation. A discussion of each test specimen and test setup follows.

Compression-B. The bolted specimens were assembled prior to exposure. The purpose of this type specimen was to provide slip data for conditions simulating a shop-bolted connection (no significant exposure prior to assembly) with maximum shear load applied at a later time in service. Three plates, 5/8 in. × 4 in. × 4 in. (16 mm × 102 mm × 102 mm) were placed in a jig to keep the plates aligned while the 7/8 A325 bolt (22 mm), Type 3 (weathering) bolts were tightened by a modified turn-of-nut method which is described later. After assembly, the connection was placed outside for continuous exposure until tested for slip load 6 or 12 months later. Bolt elongations were monitoried during exposure. As shown schematically in Figure 6a, the connection was placed in a test machine and loaded in a compressive manner until slip occurred.

Compression-HB. The connection which is shown crosshatched in Figure 6b is similar to the B specimen described above except that a hydraulic bolt is used to clamp the plates together. A threaded rod passes through a centerhole ram and is locked in position by nuts at both ends. Oil pressure is applied to the ram, which forces the drilled nut (a 7/8 2H nut (22 mm) with the threads drilled out so it can slip



(a) BOLTED SPECIMEN - B



(b) HYDRAULIC BOLT SPECIMEN - HB

Figure 6. Compression specimens (1 in. = 25.4 mm).

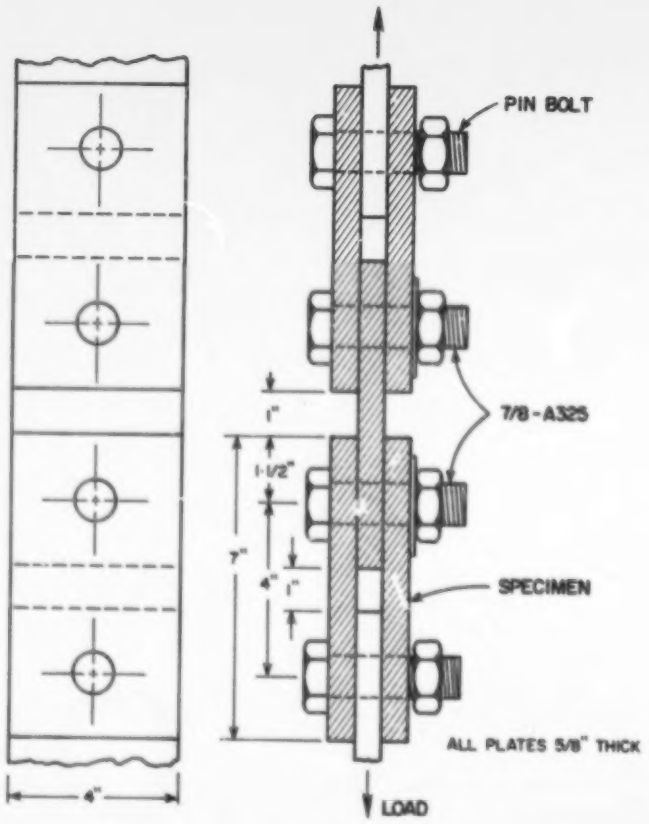


Figure 7. Bolted tension specimen-B
(1 in. = 25.4 mm)

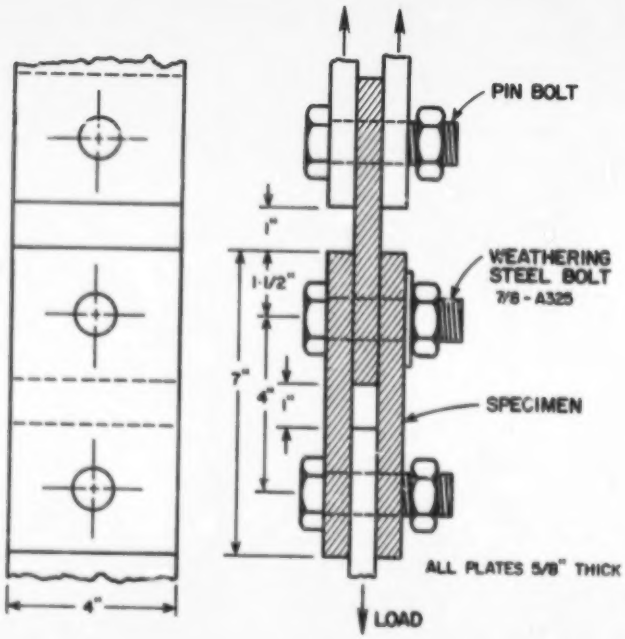


Figure 8. Bolted tension creep specimen-BC
(1 in. = 25.4 mm)

along the threaded rod) against the connection plate. The drilled nut provides the same plate contact area as a bolt. Oil pressure is increased until the desired clamping force is reached. The clamping force is easily maintained at the desired level while the test machine applies shear load to the connection. A clamping force of 39 kips (174 kN) was used, which is the minimum specified for a 7/8 A325 bolt (22 mm) [2]. The details and development of this test arrangement are described more fully in Ref. 4, where more than 600 slip tests using the HB compression test setup are reported. A photo of the HB specimen in the compression test machine is shown in Figure 9.

This test specimen was the principal one used in both the UT and FHWA programs because of its reliability and ease of testing. It was also used to simulate conditions found in field-bolted connections in which the component plates are exposed to the atmosphere for some time before assembly and the connection subjected to load reasonably soon after field bolting.

Tension-B. Three tension specimens were designed to provide a direct comparison with the slip load from the HB compression specimens with unexposed mill scale surface. The symmetrical design of the test specimen shown crosshatched in Figure 7 permits two independent slip load tests. The end fixture plate shown solid fits between the plates of the test specimen and is gripped by the tension test machine. The pin bolts are left loose for alignment.

The test specimens were assembled in an alignment jig using Type 1 (nonweathering), 7/8 A325 bolts (22 mm) with a normal hardened washer under the nut. One of the specimens had 1-1/8 in. (29 mm) diameter oversize holes in all the plies. The A325 bolt tightening procedure was the same as that used for the compression-B specimens.

Tension-BC. Twelve bolted creep specimens were fabricated as shown in Figure 8. The installation procedure for the 7/8 A325 (22 mm) weathering steel bolts was the same as that used for the other bolted specimens. The bolts were installed and then, using pin bolts, the specimens were connected in series outside in a single chain, as shown in Figure 4. The creep test setup is similar to the one described in detail in Ref. 7. Briefly, the lower end of the specimen chain was attached to a set of calibrated soft springs and the upper end to a loading fixture. The upper fixture was used to load the chain to the desired force level, and the springs reasonably maintained the load at this level as creep or slip occurred. Small adjustments were made periodically to keep the load constant.

The creep chain contained five sandblasted specimens, five mill scale specimens, and two connections with zinc-rich paint, one organic and one inorganic. Slip deformation and bolt forces were monitored for one year exposure. At the end of this period the chain was unloaded and static slip tests conducted. A typical tension BC specimen under preparation for a static slip test is shown in Figure 10. End fixtures were

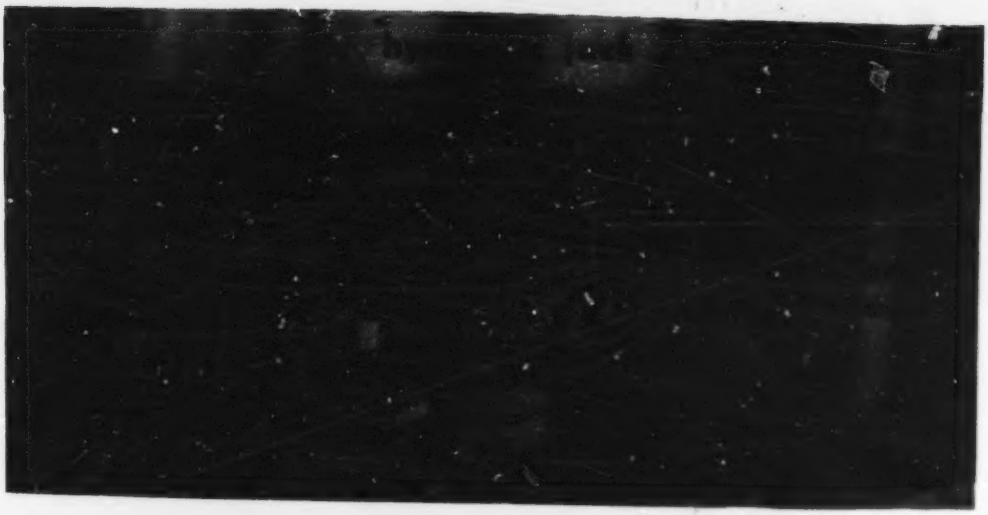


Figure 9. HB connection compression test setup

Figure 10. BC connection tension test setup

attached to the specimen so that the tension-B test setup described above could be used for the slip test.

Bolt Calibration

In the test specimens assembled with 7/8 A325 bolts (22 mm), it is necessary to establish the bolt clamping force in order to derive the slip coefficient k_s. Tests were conducted on the two bolt lots used in the program to establish the relationship between bolt tension and bolt elongation. The results from four calibrations on the 7/8 A325 (22 mm) Type 3 (weathering steel) lot, which was used for all bolted test connections except the tension-B specimens, are shown in Figure 11. The data were obtained by inserting the bolt in a Skidmore-Wilhelm load indicator and torquing the bolt in 1/8 turn increments to failure. Bolt elongations were measured with a mechanical extensometer which had a 0.0001 in. (0.0025 mm) sensitivity. The extensometer contacts rested in carefully prepared seats on the end of the bolt shank and the bolt head. The technique is described in more detail elsewhere [7]. Similar procedures for bolt calibration have been used by others [9].

Three of the calibrations shown in Figure 11 are almost identical up to an elongation of 0.08 in. (2.0 mm). Bolt No. 3 gave a lower load response. For the purpose of data evaluation, it is assumed that the average of bolts 1, 2, and 4 represents the load-elongation response of the lot. The calibrations point out one of the difficulties in determining the k_s of a joint with bolts; namely, obtaining a reliable measure of the clamping force.

To minimize variations in the clamping force in the specimens, the bolts were torqued to produce an elongation between 0.04 in. (1.0 mm) and 0.07 in. (1.8 mm). Within this range the clamping force was taken as 54.5 kips (243 kN). This range of elongation was obtained by applying about a 5/8 turn from the snug position and then sometimes a slight additional rotation to bring the bolt within the desired elongation range. Normal turn-of-nut installation practice for this grip length would require a one-third turn ±30° (between 1/4 and 5/12 turns).

The 7/8 A325 (22 mm) Type 1 (nonweathering) bolts used in the tension B specimens were calibrated in a similar fashion, and the bolts installed at elongations near the plateau of the average load-elongation response curve. The average curve based on three bolt calibrations and the measured bolt elongation were used to establish the clamping force in each specimen.

Test Procedure and Instrumentation

Slip Tests. The test procedures for compression-type slip tests and tension-sype were the same. The specimens were aligned in the test machine to minimize eccentricities. In the case of compression-type specimens, a spherical head was used to ensure uniform compression along

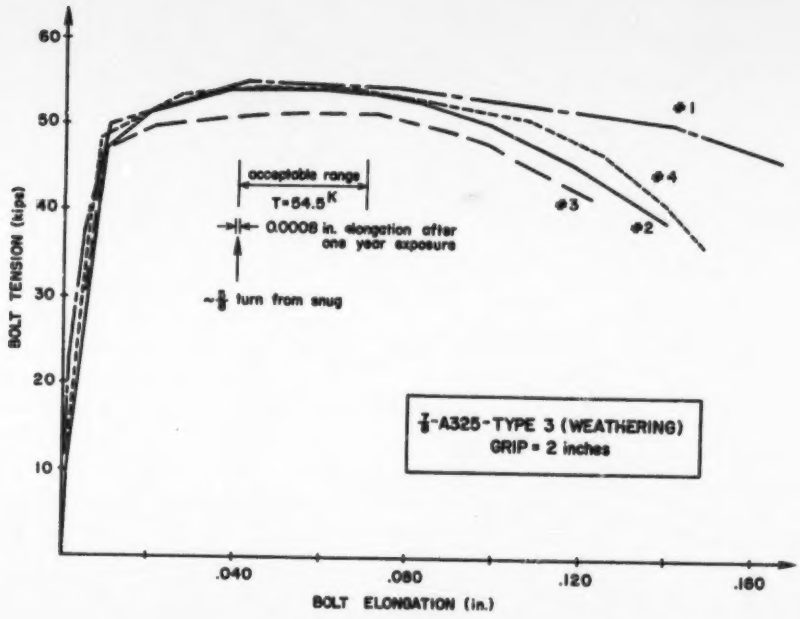


Figure 11. Bolt calibration curves (1 in. = 25.4 mm, 1 kip = 4.45 kN)

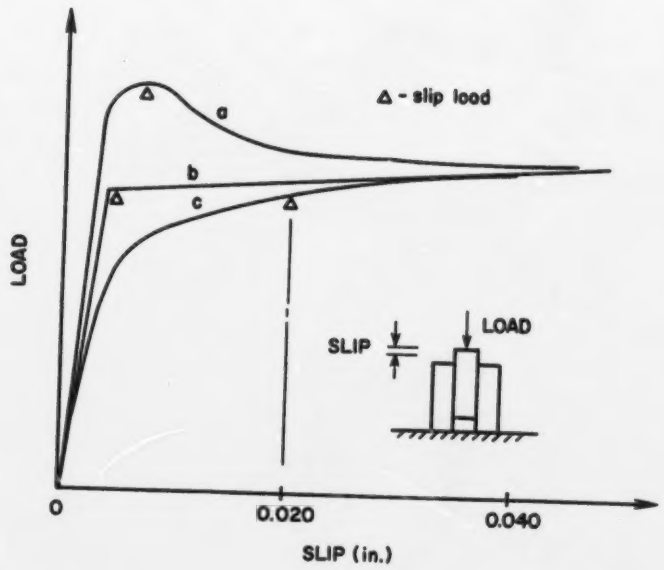


Figure 12. Definition of slip load (1 in. = 25.4 mm)

the edge of the plate. Pin bolts (see Figure 7) were used to connect the tension specimens to the end fixtures which eliminated bending in the specimen. Slip gages were attached to the specimen with set screws as shown in Figures 9 and 10. Linear potentiometers or DCDT's were located on each side of the specimen and connected in a manner to give the average of the two readings. The gages measured the relative displacement (slip) between the interior connection plate and the two side plates. The slip and the load applied to the specimen were plotted automatically using an X-Y recorder. The applied loading rate was approximately 25 kips (111 kN) per minute or 0.003 in. (0.076 mm) of slip per minute. The test was terminated when a total slip reached approximately 1/16 in. (1.6 mm), the nominal hole clearance.

The slip load was determined from the connection load-deflection plot, some typical types of which are shown in Figure 12. The slip load was recorded as one of the following:

(a) The maximum load provided this maximum occurred before a total slip of 0.020 in. (0.51 mm) occurred, as shown in Figure 12.

(b) The load at which the deflection rate suddenly increases, typically as shown by curve b.

(c) The load measured when the slip is 0.020 in. (0.51 mm). This definition controls when the load-deflection curves shows a gradual change in response, as shown by curve c.

Creep Tests. The 1978 AASHTO Bridge Specifications permits a maximum calculated bolt shear stress of 16.5 ksi (114 MPa) for mill scale surfaces as shown in Table 1. For a 7/8 in. (22 mm) diameter bolt in double shear, this shear stress level corresponds to a load of 19.8 kips (88.1 kN). Since five of the twelve creep specimens had mill scale surfaces and the remaining seven specimens with blasted and zinc-rich paint surface conditions permitted shear stresses greater than 16.5 ksi (114 MPa), it was decided to maintain the load in creep chain at the maximum 16.5 ksi (114 MPa) bolt stress level. The first increment of load was applied on 8/2/77 to produce a bolt shear stress of 12.5 ksi (86 MPa), 75 percent of the maximum desired level. This stress level was maintained approximately one month until 9/7/77, when the bolt shear stresses were increased to 16.5 ksi (114 MPa), and maintained at this level until the chain was dismantled about one year later on 9/21/78.

Loads were applied through a loading fixture using a hydraulic ram. The loads were fixed into the chain by a locking nut, and 0.001 in. (0.025 mm) dial gages measuring the end spring deflection were recorded. These deflection gages were monitored weekly and if changes in the spring deflection indicated a change in the load of more than 300 lb. (1.33 kN) (0.25 ksi [1.7 MPa] bolt shear stress) adjustments were made to bring the load up to the desired level.

Creep deformation was recorded as the relative shear movement between the inside plate and the two outer plates of the creep connection shown in Figure 8. Short pieces of 1/8 × 3/4 × 3/4 in. (3.1 mm × 19 mm × 19 mm) angle were tack-welded to the edges of the plates so that a gage distance of approximately 1-7/8 in. to 2 in. (48 mm to 51 mm) was maintained. A 0.0001 in. (0.0025 mm) micrometer was used to measure the distance between the 5/32 in. (4.0 mm) diameter ball bearings glued to the tabs, as depicted in Figure 13. Readings were taken on both sides of the specimen and the average was recorded as the creep deformation. The creep gages used provided deformation data reliable to ±0.0004 in. (0.010 mm) [7]. Creep measurements were taken when the load was applied and about one hour after to detect "instantaneous" creep. Thereafter, readings were taken periodically, depending on the amount of creep detected. When creep was apparent, data were recorded every few days; when no creep was detected, data were taken very few months.

Bolt Forces. The change in bolt elongation was monitored in the exposed specimens. The bolt length was recorded after assembly using the mechanical extensometer described in the section, Bolt Calibration, and shown in Figure 14. The length of an unassembled bolt was also recorded as the standard gage to account for changes in the extensometer and temperature. The elongations of the standard gage bolt and the connection bolts were recorded again when the connections were prepared for the slip tests, either six months or one year later. The bolt elongations could then be converted to bolt forces using the bolt calibration curves described earlier.

Figure 13. Creep instrumentation

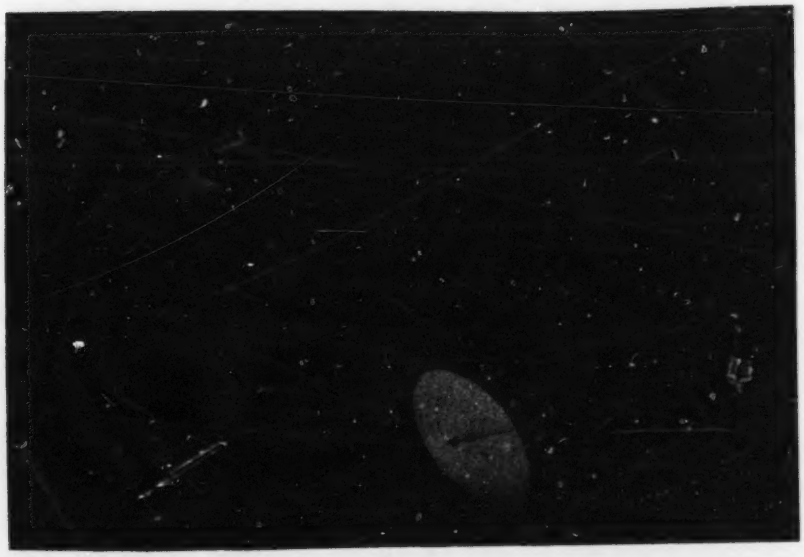


Figure 14. Bolt elongation measuring device

3. TEST RESULTS AND DISCUSSION

Static Slip Tests

A summary of the 126 slip tests is presented in Table 2. Two of the tests were on painted surfaces, 69 had blasted contact surfaces, and 55 had mill scale surfaces. The type of test and steel identify have been discussed in previous sections. In all B and BC type tests, the plates were assembled in the final connection with 7/8 A325 (22 mm) bolts prior to exposure; in the HB tests, the plates were exposed in the unassembled state. The number of tests listed in each category are on different replicate connections. The slip coefficients were calculated using Eq. 1, based on the slip loads as defined in Figure 12. Standard deviations are given only when four or more replicates were tested. The slip coefficients are given only to two decimal places because the authors feel that further refinement is unjustified due to the experimental scatter.

Mill Scale Surfaces. Five different heats from two grades of A588 steel were tested in the unweathered state. The k_s for the five heats taken from Table 2 are A1 - 0.20, A2 - 0.26, A3 - 0.28, B1 - 0.23, and B2 - 0.23. Treating these give averages as individual samples, the average k_s for all heats is 0.24. If the 31 slip tests are treated as individual samples, the average k_s is 0.23 (standard deviation = 0.034), a slight reduction from the average of the heats because 11 tests were conducted on steel A1 and 5 tests on each of the other heats. The average k_s are 0.25 and 0.23 for Grades A and B, respectively. The six tension tests and five HB compression tests on the A1 steel gave the same average k_s, indicating the type of test has no effect.

There was no difference in the experimental k_s for standard and oversize holes with a mill scale surface. This was due to the fact that a modified turn-of-nut method was used, resulting in the same clamping force for both conditions. Using standard tightening techniques, a lower clamping force, and consequently a lower slip load, would be expected [1].

These average k_s for A588 steel are significantly lower than the average for mill scale surfaces reported by Fisher and Struik [1]. Their summary of 312 slip coefficients from tests on mill scale surfaces for steel with specified yield strengths of 50 ksi (345 MPa) or less is shown in Figure 15. The mean slip coefficient which was used to establish the allowable stress in the Bolt Spec is 0.34. They found no significant difference between steels with yield points of 50 ksi and 36 ksi. The 31 test results for A588 steel are shown in black in Figure 15, and they all are lower than the mean for other steels. The data suggest that the current allowable stress in the Bolt Spec is not applicable to A588 steel. The average k_s for A588 steel is only 68 percent of the value for other steels. Further discussion will be presented in a subsequent section dealing with design recommendations.

Table 2. Summary of slip test results

Surface Condition (1)	Type of Test (2)	Steel Identity (3)	Months Exposed (4)	Number of Tests (5)	Average Slip Coefficient (6)	Standard Deviation (7)
			University of Texas Tests			
M. Scale	Tens.-B	A1	0	4	0.20	0.015
M. Scale	Tens.-B	A1	0	2*	0.20	-
M. Scale	Tens.-BC	A1	12	5	0.29**	0.019
Sand Bl.	Tens.-BC	A1	12	4	0.65	0.047
Inorg. Zinc	Tens.-BC	A1	12	1	0.67	-
Org. Zinc	Tens.-BC	A1	12	1	0.52**	-
M. Scale	Comp.-HB	A1	0	5	0.20	0.009
Sand Bl.	Comp.-HB	A1	0	5	0.86	0.038
M. Scale	Comp.-HB	A1	6	4	0.27	0.009
M. Scale	Comp.-B	A1	6	5	0.18	0.004
M. Scale	Comp.-HB	A1	12	5	0.37	0.068
M. Scale	Comp.-B	A1	12	5	0.19	0.011
Sand Bl.	Comp.-HB	A1	6	5	0.74	0.043
Sand Bl.	Comp.-B	A1	6	5	0.77	0.035
Sand Bl.	Comp.-HB	A1	12	5	0.59	0.080
Sand Bl.	Comp.-B	A1	12	5	0.75	0.020
			Federal Highway Administration Tests			
M. Scale	Comp.-HB	A2	0	5	0.26	0.016
M. Scale	Comp.-HB	A3	0	5	0.28	0.008
M. Scale	Comp.-HB	B1	0	5	0.23	0.019
M. Scale	Comp.-HB	B2	0	5	0.23	0.016
Grit Bl.	Comp.-HB	A2	0	5	0.59	0.083
Grit Bl.	Comp.-HB	A3	0	5	0.38	0.018
Grit Bl.	Comp.-HB	B1	0	5	0.50	0.078
Grit Bl.	Comp.-HB	B2	0	5	0.60	0.047
Grit Bl.	Comp.-HB	A2	3	5	0.78	0.078
Grit Bl.	Comp.-HB	A3	3	5	0.87	0.063
Grit Bl.	Comp.-HB	B1	3	5	0.86	0.073
Grit Bl.	Comp.-HB	B2	3	5	0.83	0.042

*1-1/8 in. (29 mm) diameter holes. All other specimens had 15/16 in. (24 mm) diameter holes.
**Previously slipped into bearing during creep experiment.

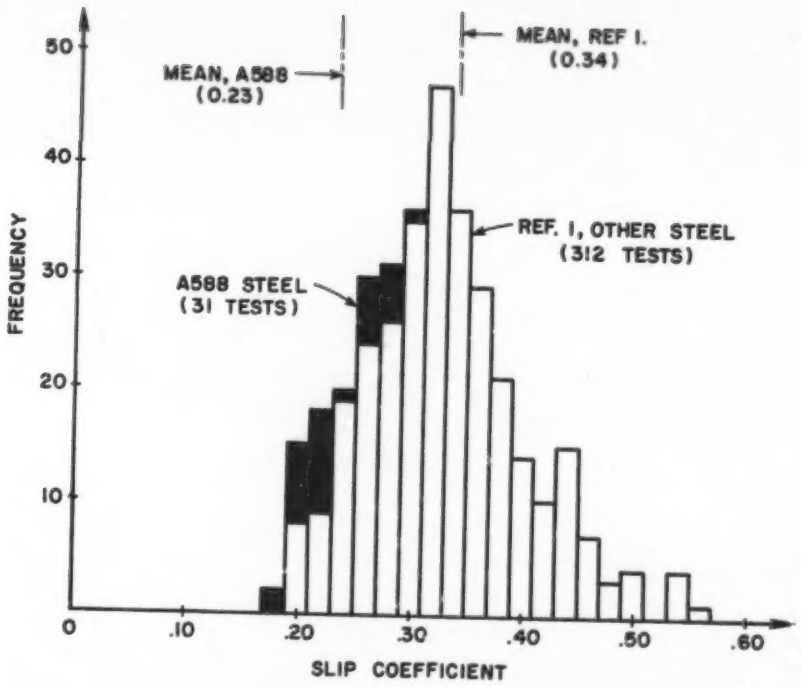


Figure 15. Distribution of slip coefficient for clean mill scale

Blasted Surfaces. The 25 unweathered blasted specimens gave a mean k_s = 0.58 with a standard deviation (s.d.) of 0.17. This standard deviation is quite large and is caused by combining the results of the 5 sandblasted specimens (mean k_s = 0.86, s.d. = 0.04) and the 20 grit-blasted specimens (mean k_s = 0.52, s.d. = 0.10). The type of blasting had a significant effect on the surface roughness. Considering the scatter within the replicates for the four heats of grit-blasted specimens, there is no significant effect of A588 steel grade on k_s.

Since only one heat of steel was sandblasted, there is insufficient data to suggest that all sandblasted A588 steels have a typical k_s in excess of 0.8, which is the highest k_s reported in the literature. Fouad [4] tested 103 sandblasted specimens with three different steels (A36, F_y = 36 ksi [248 MPa]; A572, F_y = 50 ksi [345 MPa]; A514, F_y = 100 ksi [690 MPa]) with an average k_s = 0.521, which is similar to the average value reported by Fisher and Struik [1], k_s = 0.49 for 163 tests on mild carbon steel which were grit or sandblasted. These data show that the type of blasting does not significantly affect the slip characteristics of nonweathering steels. Until additional test data are available on sandblasted A588 steel, it is recommended that no distinction be made between sandblasted and grit-blasted A588 steel and that a k_s of 0.5 be considered appropriate for all blasted steel surfaces.

Effect of Exposure. With three months exposure, the four heats of grit-blasted A588 tested by the FHWA showed a 60 percent increase in the average k_s, from 0.52 to 0.83. The sandblasted HB specimens exposed in Austin showed a decrease in k_s with increased exposure, 0.86, 0.74, and 0.59 for zero, six, and twelve months exposure, respectively, as shown by a solid line in Figure 16. Other data taken from Table 2 are also shown. Each data point represents the average of five tests. Specimens bolted up during exposure (B) showed little change over twelve months. No bolted specimens were tested initially, but the values of k_s for the HB specimens can be used for zero exposure. Examination of the B specimens after testing indicated very little surface corrosion on the faying surfaces. The mill scale plates (HB) visually showed the results of 12 months exposure and they also "felt rough" compared to the unexposed plates. After 12 months, the average k_s for the HB mill scale plates increased from 0.20 to 0.37.

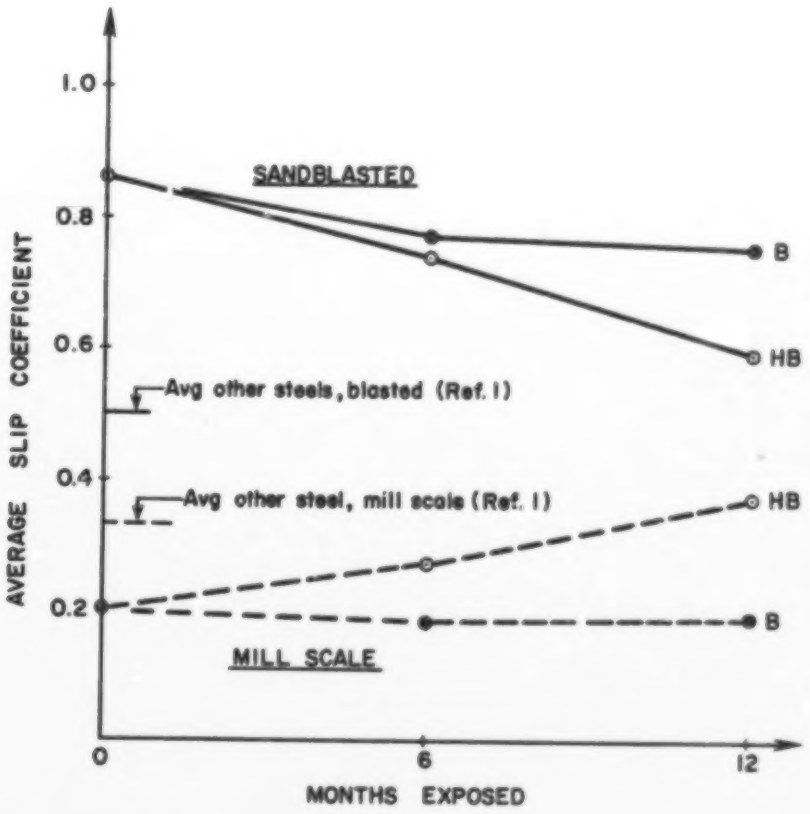


Figure 16. Effect of exposure on slip resistance

The sandblasted BC tension slip specimens gave an average k_s of 0.65 after 12 months of exposure under load in the creep chain. This k_s is 15 percent lower than the results from the compression B specimens which were exposed a similar amount but not under shear load. Examination of the faying surfaces after testing indicated the stressed connections (BC) weathered at a faster rate than the unloaded connections (B). The B and the BC specimens gave higher k_s than the HB plates which were unassembled and showed significant weathering after 12 months exposure.

The slip coefficient for the mill scale BC tension specimens exposed for 12 months gave a slip coefficient of 0.29 assuming two shear planes as in all other tests. However, this value cannot be compared to the compression B specimen results for 12 months exposure because these creep specimens had already slipped into bearing during the creep experiment as described later. The k_s shown in Table 2 represents the slip of the outer plates of the connection relative to the bolt head and nut and the interior plate. Thus, there are more than two shear planes developed; the slip load for this condition should be higher than that required for initial slip into bearing.

The test results show contradictory trends for exposed grit-blasted and exposed sandblasted plates. It could be reasoned that surface corrosion deteriorated the rough unweathered surface profile of the sandblasted plates which had developed very high k_s, whereas the initial surface was much smoother for the grit-blasted plates which was further roughened by the weathering.

Tests are currently underway in England on the effect of exposure. Results after one year of exposure reported by Moss [9] indicate that weathering improved the slip coefficient of grit-blasted plates for both Grade 50 steel and weathering steel. The initial slip coefficients for the two steels, 0.42 and 0.37, respectively, which are below the 0.50 average reported previously for blast-cleaned surfaces were improved to 0.52 and 0.49 by exposure.

These test data indicate that surface exposure of A588 steel up to one year prior to connection assembly does not produce k_s less than the average value for clean-blasted surfaces of other steels. Exposure improved the slip resistance of A588 mill scale surfaces. However, it took 10 months of exposure prior to assembly to increase k_s to 0.34, the average value for mill scale surfaces of other steels. It would normally be expected that the steel be exposed only a few months before assembly. Since the exposure effect is almost linear, as shown in Figure 16, a few months exposure will not significantly improve the slip load.

Creep Tests

All twelve specimens in the single creep chain were subjected to the same load history summarized in Table 3. The maximum load applied

Table 3. Creep chain load history

Load Stage	Date	Load (kips)	Bolt Shear Stress (ksi)	Notes
1	8/2/77	0	0	Start of test
2	8/2/77	5.00	4.16	Held for two hours
3	8/2/77	10.00	8.32	Held for one hour
4	8/2/77	15.00	12.47	Held for 36 days
5	9/7/77	16.30	13.55	Held for one hour
6	9/7/77	17.50	14.55	Held for one-half hour
7	9/7/77	19.84	16.50	Held for 379 days
8	9/21/78	0	0	Chain dismantled

*(1 kip = 4.45 kN, 1 ksi = 6.9 MPa)

corresponded to a bolt shear stress of 16.5 ksi (114 MPa), the allowable stress for a friction-type bolted connection with mill scale surfaces given in the AASHTO Bridge Specifications [3]. This maximum load was 91 percent of the average expected slip load, based on the mean k_s = 0.20 for the steel identified as A1 and the measured bolt-clamping force of 54.5 kips (243 kN).

The load on the chain was applied in three stages until the nominal bolt shear stress was 12.5 ksi (86 MPa). No significant deformation, less than 0.001 in. (0.025 mm), was recorded until the load reached 15 kips (67 kN). At this load a loud bang was heard and the creep gages indicated slip in the organic zinc specimen of 0.003 in. (0.076 mm) and in one mill scale specimen of 0.009 in. (0.228 mm). The 12.5 ksi (86 MPa) bolt shear stress was maintained for 36 days (865 hours) and the slip gages indicated no significant additional movement except in the organic zinc specimen. This modified phenoxy paint had been applied in two coats for a total average thickness of 5 mils (0.127 mm) on each plate surface. The total paint thickness on a contact surface was 10 mils (0.25 mm). The deformation-time response for this specimen, shown in Figure 17, indicates continuous creep until approximately 300 hours elapsed. Then, the creep rate significantly reduced. At this time, the creep recorded was more than one-half of the theoretical 1/16 in. (1.6 mm) hole clearance.

An explanation for the rate change is that a possible bearing contact took place. Slight hole misalignment, paint in the bolt hole, and lack of opposite bearing contact during assembly could account for premature bearing. The slip test on this specimen after the chain was

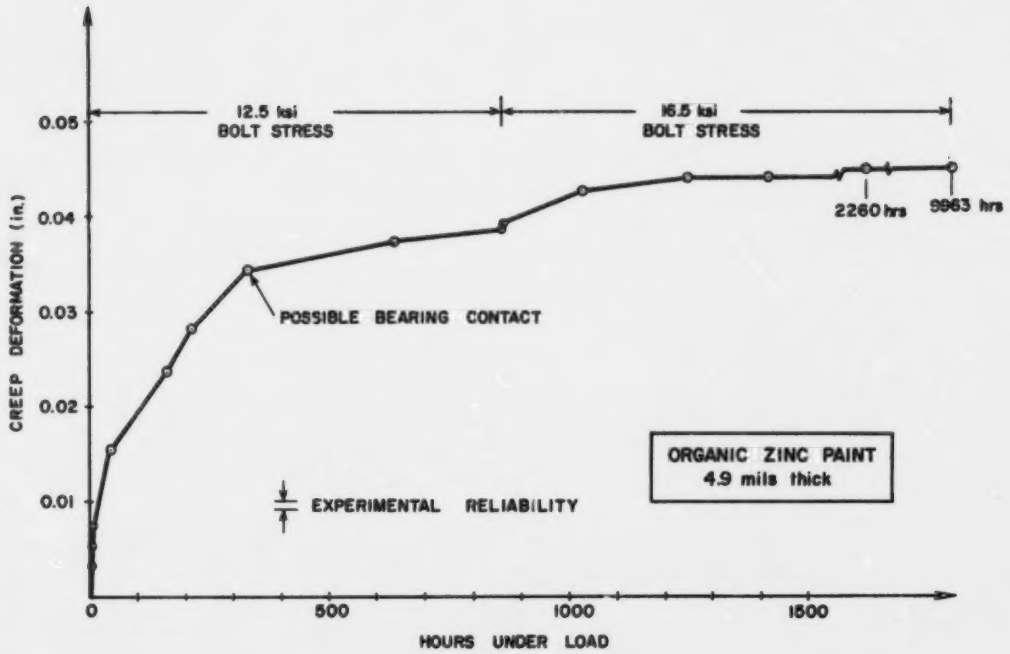


Figure 17. Creep-time response, organic zinc specimen
(1 in. = 25.4 mm)

dismantled at 9963 hours showed relatively no horizontal slip plateau of the type shown in Fig. 12. The slip response was somewhat like curve b of that figure, but with the "horizontal" line about six times steeper. This indicates that bearing did take place.

After 36 days at 12.5 ksi (86 MPa) bolt stress, the load was increased in three stages to produce a stress of 16.5 ksi (114 MPa). During the first stage, two distinct bangs were recorded and the slip gages indicated two mill scale specimens each moved 0.005 in. (0.127 mm); one connection was the same one that slipped previously. No further movement occurred while the bolt stress was held at 13.5 ksi (93.4 MPa) for one hour, and increased to the desired level of 16.5 ksi (114 MPa). After two hours at 16.5 ksi (114 MPa), all five mill scale specimens slipped suddenly into bearing with loud reports. The average movement was 0.065 in. (1.65 mm), which is approximately 1/16 in. (1.6 mm).

During the one year creep experiment, the sandblasted and inorganic zinc specimens, which were subjected to shear loads equal to 55 percent of their slip loads, showed no significant (< 0.001 in. or 0.025 mm) creep or slip. The mill scale specimens did slip suddenly into bearing as described previously because the applied loads were at 92 percent of the average slip loads. An examination of the individual slip tests on unexposed mill scale surfaces showed come connections slipped at loads slightly lower than those applied to the creep chain. Because of the small range in the k_s for eleven A1 steel specimens (0.18 to 0.22) for both tension and compression tests on unweathered mill scale, it would

be expected that the dynamic effect caused by slip in one specimen could trigger slip in the remaining connections.

Creep did occur in the organic zinc specimen at a bolt shear stress level of 12.5 ksi (86 MPa), which was approximately 25 percent of the slip level and only 66 percent of the allowable stress permitted by the AASHTO Specification as shown in Table 1. This single test does not follow the creep results on the same paint reported by Nanninga [7]. After more than 1000 hours at higher shear stresses of 21.4 ksi (148 MPa) insignificant movements of approximately 0.001 in. (0.025 mm) were recorded in twelve connections. The difference between these two sets of data cannot be adequately explained. Nanninga's tests were conducted indoors, whereas the single test reported herein was exposed outside. Perhaps higher temperatures on the outside specimen promoted the creep. While a single test result is not sufficient to develop broad recommendations, it should not be dismissed either. Further creep tests should be conducted on exposed specimens with organic zinc paint. In the meantime, organic zinc paint on the faying surfaces of friction connections with significant sustained loads should be used with caution.

Bolt Elongations

The measured changes in bolt lengths after twelve months of exposure for twenty unpainted specimens and two painted specimens is given in Table 4. The changes measured after six months were too small to be

Table 4. Change in bolt length after twelve months exposure in inches (1 in. = 25.4 mm)

Specimen Type	Surface	Elongation (in.)
Tension-BC	Mill Scale	+0.0009
	Sand Bl.	+0.0005
	Inorg. Zinc	-0.0009
	Org. Zinc	-0.0010
Compression-B	Mill Scale	+0.0008
	Sand Bl.	+0.0008

reliable considering the sensitivity of measuring device shown in Figure 14. All the bolts in the unpainted mill scale and sand-blasted specimens showed increases in length consistent with weathering of the faying surfaces. There is no reliable significant difference between the tension and compression specimens. The bolts in the painted specimens

showed decreases in length due to creep in the paint in the direction of the clamping force. The loss in clamping force corresponding to a reduction in length of 0.0009 in. (0.023 mm), assuming elastic unloading and using the bolt calibration data plotted in Figure 11, is approximately 5 kips (22 kN) or 9 percent of the initial clamping force of 54.5 kips (243 kN). The k_s for the two painted specimens given in Table 2 are based on the reduced clamping force of 49.5 kips (220 kN). Relaxation of the bolt clamping force due to paint creep has been reported by others [7,10].

One concern in unpainted joints is the possibility of corrosion on the faying surface causing an increase in the bolt elongation so that the bolt fails in tension. The average increase in elongation recorded for unpainted surfaces of 0.0008 in. (0.020 mm) is shown on the bolt calibration plot in Figure 11. Because of the ductility of the A325 bolt, it would take about 100 years of constant increases of this level of elongation to fail the bolts. However, due to the claimed weathering mechanism of A588 steel, the rate of weathering would not remain constant over this period of time. It can, therefore, be concluded that faying surface weathering will not adversely affect the bolt performance in A588 steel connections in which the bolts are placed in compact patterns. If bolts are widely spaced such that some plate material is not in good contact, it may be possible that expansion at the faying surface due to corrosion would cause some prying forces on the bolt. This possibility was not considered in the research project and would not be of concern in typical friction-type shear connections in bridge structures.

4. DESIGN RECOMMENDATIONS AND COMMENTS

In the 1966 Bolt Specification [2a], the allowable bolt shear stress of 15 ksi (103 MPa) for mill scale surfaces was based on a k_s = 0.35, the minimum specified clamping force, and a factor of safety of 1.51. In building structures, there has been almost twenty years of satisfactory connection performance using this stress level. Data collected since then give an average k_s for mill scale = 0.336 [1], so that the factor of safety using the 1966 stress level would be 1.45. In 1976, the Bolt Spec increased the allowable stress to 17.5 ksi (121 MPa), mainly on the basis of laboratory data which indicated that the clamping force for calibrated wrench tightening would be typically 13 percent higher than the minimum specified.

In the authors' opinion, the possible increase above the minimum specified clamping force should not be considered in the development of design recommendations for the following reasons:

1. The statistics which indicate higher than minimum specified clamping have typically been developed from laboratory data, with the bolts tightened carefully by researchers. This may not be representative of actual field installation by fabricators and erectors.

2. Much of the turn-of-nut data was based on one-half turn from snug but current specifications would permit many of these bolts to be tightened to one-third turn, resulting in a lower clamping force.

3. Tension control techniques such as load indicator washers produce results closer to the minimum specified clamping force which should be acceptable.

4. Losses in bolt clamping force due to paint creep.

A factor of safety of 1.45 with the minimum specified clamping and the mean k_s from the tests reported herein is used to develop the design recommendations for A588 steel. For mill scale surfaces with k_s = 0.23, the allowable stress is 10 ksi (69 MPa) with A325 bolts. For blasted surfaces, using k_s = 0.52 typical of the grit blasting, the allowable stress is 23 ksi (159 MPa). There is considerable structural advantage to blast clean the faying surfaces of A588 steel. The allowable stresses would be valid for plates exposed for up to one year prior to assembly. There should be no difference between the k_s of painted A588 steel and other steels with the same paint. The use of organic zinc paint with sustained loads on the faying surface should be limited in friction-type connections until additional data are generated.

The specific changes required in the AASHTO Bridge Specification to accommodate these recommendations for A588 steel are given in Appendix A.

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APPENDIX A. RECOMMENDED CHANGES IN THE 1978 INTERIM AASHTO BRIDGE SPECIFICATION

Table 1.7.41C1—Allowable Working Stresses For High Strength Bolts[a] in ksi (MPa).

Load Condition	Hole Type	AASHTO M164[f] (ASTM A325) Bolts	AASHTO M253 (ASTM A490) Bolts
Applied Tension[b] (T)	Standard, oversize or slotted	39.5 (272.342)	48.5 (334.395)
Shear (F_v): Friction-Type Connection[c]	Standard	16.0 (110.316)	20.0 (137.895)
	Oversize	13.5 (93.079)	17.0 (117.211)
	Short slotted	13.5 (93.079)	17.0 (117.211)
	Long slotted	11.5 (79.289)	14.5 (99.973)
Shear (F_v): Bearing-Type Connection:[d]			
Threads in any shear plane	Standard or slotted	19.0 (131.000)	25.0 (172.369)
No threads in shear plane	Standard or slotted	27.0 (186.158)	36.0 (248.211)
Bearing[e] (f_p)	Standard or slotted	$\frac{LFu}{2.2d}$ or 1.35 Fu (whichever is smaller)	

for all steels except A588. See Class J in Table 1.7.41C2 for A588 mill scale surfaces.

[a] The tabulated stresses, except for bearing stress, apply to the nominal area of bolts used in any grade of steel.

[b] For allowable working stresses when bolts are subjected to fatigue loading in tension, see Article 1.7.41(C)(4).

[c] Applicable for contact surfaces with clean mill scale. When the designer has specified special treatment of the contact surfaces in a friction-type connection, values in Table 1.7.41(C)(2) may be substituted.

[d] In bearing-type connections whose length between extreme fasteners in each of the spliced parts measured parallel to the line of an axial force exceeds 50 inches (1.27m), tabulated valued shall be reduced by 20 percent.

[e] L is the distance in inches (m) measured in the line of force from the center line of a bolt to the nearest edge of an adjacent bolt or to the end of the connected part toward which the force is directed; d is the diameter of the bolts; and Fu is the lowest specified minimum tensile strength of the connected parts.

[f] AASHTO M164 (ASTM A325) high strength bolts are available in three types, designated as types 1, 2 or 3. Type 3 shall be required on the plans when using unpainted AASHTO M222 (ASTM A588) steel.

Table 1.7.41C2—Allowable Working Shear Stresses[a] for High Strength Bolts Used for Friction-Type Shear Connectors. Based Upon Surface Condition of Bolted Parts, in ksi (MPa).

Class of Surface[b]	Surface Condition of Bolted Parts	Standard Holes		Oversize Holes and Short Slotted Holes		Long Slotted Holes	
		M164 (A325)	M253 (A490)	M164 (A325)	M253 (A490)	M164 (A325)	M253 (A490)
A	Clean mill scale	16.0 (110.316)	20.0 (137.895)	13.5 (93.079)	17.0 (117.211)	11.5 (79.289)	14.5 (99.973)
B	Blast-cleaned carbon and low alloy steel	25.0 (172.369)	31.0 (213.737)	21.0 (144.790)	26.5 (182.710)	17.5 (120.658)	21.5 (148.237)
C	Blast-cleaned quenched and tempered steel	17.0 (117.211)	21.0 (144.790)	14.5 (99.973)	18.0 (124.105)	12.0 (82.737)	15.0 (103.421)
D	Hot-dip galvanized and roughened	19.5 (134.447)	24.5 (168.921)	16.5 (113.763)	20.5 (141.342)	13.5 (93.079)	17.0 (117.211)
E	Blast-cleaned, organic zinc rich paint	19.0 (131.000)	23.5 (162.026)	16.0 (110.316)	20.0 (137.895)	13.0 (89.632)	16.0 (110.316)
F	Blast-cleaned, inorganic zinc rich paint	26.5 (182.710)	33.5 (230.974)	22.5 (155.131)	28.5 (196.500)	18.5 (127.552)	23.5 (162.026)
G	Blast-cleaned, metallized with zinc	26.5 (182.710)	33.5 (230.974)	22.5 (155.131)	28.5 (196.500)	18.5 (127.552)	23.5 (162.026)
H	Blast-cleaned, metallized with aluminum	27.0 (186.158)	34.0 (234.421)	23.0 (158.579)	29.0 (199.948)	19.0 (131.000)	24.0 (165.474)
I	Vinyl Wash	15.0 (103.421)	18.5 (127.552)	12.5 (86.184)	16.0 (110.316)	10.5 (72.394)	13.0 (89.632)

[a] Values from this table are applicable only when they do not exceed the lowest appropriate allowable working stresses for bearing-type connections, taking into account the position of threads relative to shear planes and, if required, the 20% reduction due to joint length. (See Table 1.7.41C1 Footnote d)

[b] See Article 2.10.20(C) for further definition of Class of Surface.

Except A588 steel, See Class J.

Add Class J as follows:

J	A588 clean mill scale	10.0 (68.947)	13.0 (89.631)	8.5 (58.605)	11.0 (75.842)	7.0 (48.263)	9.5 (65.500)

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

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Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

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Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.